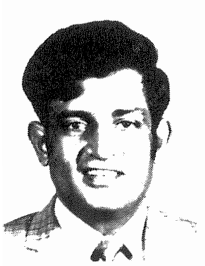
COMMISSIONING A GAS TURBINE-COMPRESSOR OR SINGLE LIFT PACKAGE FOR OFFSHORE GAS REINJECTION APPLICATIONS

by

Ramada Reddy

Head of Aerodynamic Analysis
Dresser-Clark Division
Dresser Industries, Inc.



Mr. Ramana Reddy has been with Dresser-Clark Division, Houston, since November 1968 as Head of Aerodynamic Analysis. He was with the Design and Development Group of Avco Lycoming Division, Stratford, Connecticut, for two years; for four years with Escher Wyss A. G., Zurich, Switzerland, in their Industrial Research Department of Turbomachinery; and about one year with Hindustan Aeronautics, India. He is a member of ASME and holds an M.S. (Aero) from Indian Institute of Science, India.

ABSTRACT

Sixteen centrifugal stages in two cases driven by a Rolls Royce AVON jet and a single stage power turbine compress natural gas of Mol Weight 23 from a pressure of 65 to 2000 psia. The rotating train, the coolers, the scrubbers and all systems mounted on a double-deck platform weighing 200 tons is pumping gas in the Lake Maracaibo, Venezuela, since February 1972. This paper deals with design concepts, protective devices, pre-testing of package simulating field conditions, and initial problems encountered during commissioning the unit.

INTRODUCTION

Platforms for gas lift and reinjection application have been built for many years for offshore and onshore applications, but most of these, reciprocating and centrifugal units, were assembled on site.

To the best of our knowledge, the platform package described here is the first of its kind to be designed as a "single lift package," manufactured, assembled, and load tested at the factory slip by one manufacturer within its own facility capabilities. This package is the first unit running continuously on Lake Maracaibo at a discharge pressure of 2000 psia which contains an aircraft derivative gas generator, power turbine combination coupled with two high pressure barrel compressors.

The complete plant was designed to compress 52 MMSCFD of 23.4 mol weight natural gas from 65 psia to 1815 psia which has a nominal horsepower requirement of 13,000 BHP. It is capable of being controlled remotely from shore or locally automatically or manually. This "single lift package" with its own electric generator was pre-tested in Dresser facility, shipped on a barge and set on piles in the field.

This paper describes the package and conclusions drawn as a result of the experience gained from commissioning this unit.

NOMENCLATURE

PCV	=	Pressure control valve—See Figure 1.
TCV	=	Temperature control valve—See Figure 1.
RCV	=	Recycle valve—See Figure 1.
S1	=	Scrubbers—See Figure 1.
S2	=	Scrubbers—See Figure 1.
S3	=	Scrubbers—See Figure 1.
S4	=	Scrubbers—See Figure 1.
IC 1	=	Intercoolers—See Figure 1.
IC 2	=	Intercoolers—See Figure 1.
AC	=	Aftercoolers—See Figure 1.
GG	=	Gas Generator
PT	=	Power Turbine

PROCESS FLOW SCHEMATIC

Figure 1 illustrates the arrangement of rotating train and process flow equipment schematically.

Natural gas enters the scrubber S1 through a station flow measuring orifice and an inlet valve. The pressure control valve, PCV, controls the inlet pressure to the Dresser Clark Model 553B6 compressor and maintains it at 50 psig by sensing the pressure at the inlet of 553B compressor. The 6-stage compressor compresses gas to 350 psia. The fin fan intercooler IC 1 reduces the gas temperature to 115°F. The scrubber S2 "knocks out" any heavy ends of the gas and the first six stages of 272B6-4 compressor rises the gas pressure to 980 psia. The last four stages of 272B compressor raises the intercooled and scrubbed gas to 1815 psia. The aftercooler cools the gas to 105°F before it enters the scrubber S4 and glycol dehydrating unit. The gas then joins the discharge header through a measuring orifice, a check valve, and a station discharge valve. The glycol dehydrator can be bypassed by manual operation of the valves. The recycle valves, RCV 1 and RCV 2, were designed to pass the design flow in order to facilitate full load testing of the whole platform in closed loops in addition to their function as surge control valves.

When the unit is on recycle, the temperature drop across the recycle valve, RCV 2, due to Joule Thompson Effect is on the order of 100°F. The inlet temperature of 272B compressor would rapidly reach below that of freezing point of water and thus increase the possibility of hydrate formations. To avoid this, a thermal control valve, TCV, which bypasses the required quantity of hot gases to the inlet of RCV 2, is installed.

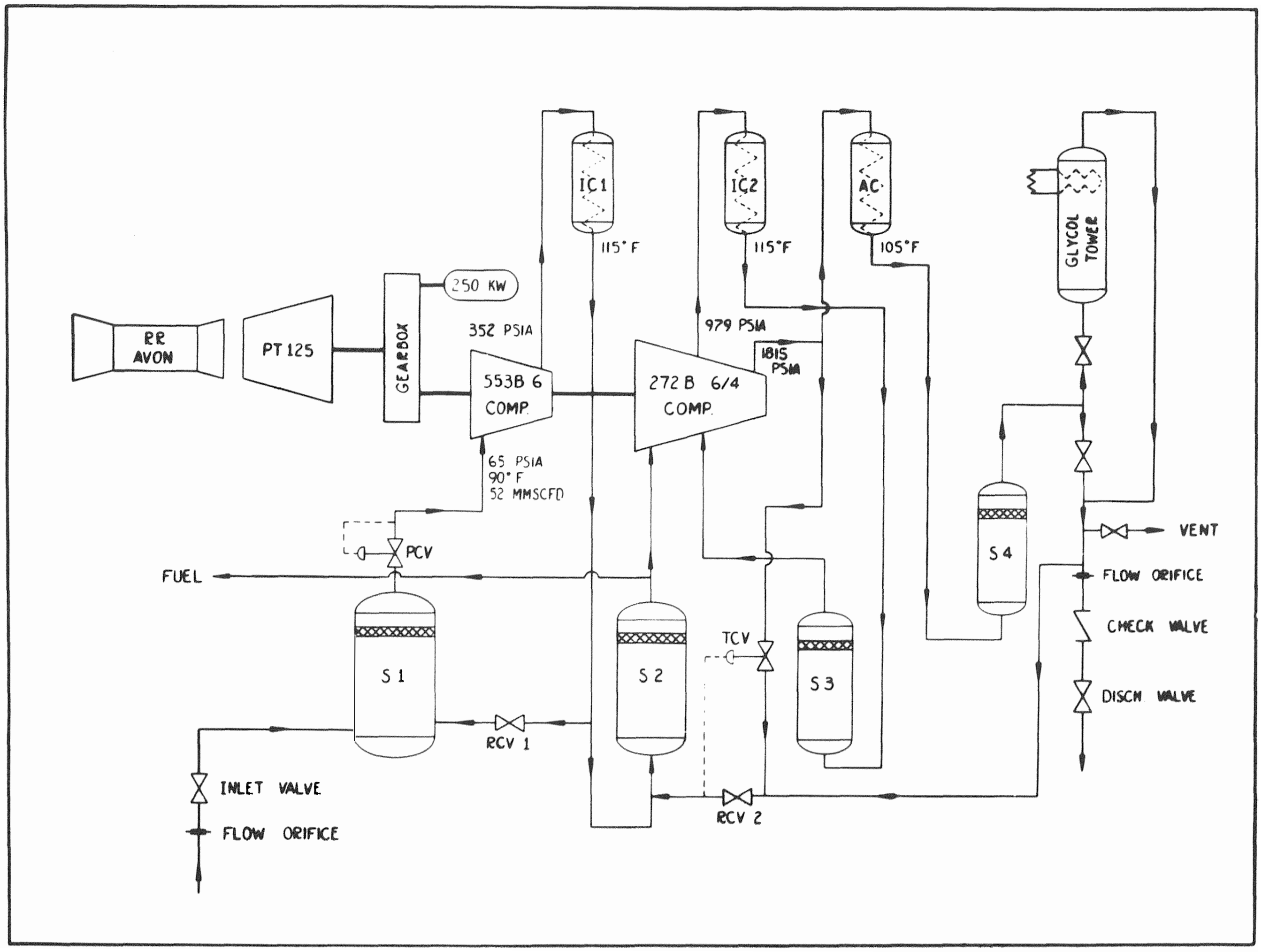


Figure 1. Schematic of Process Flow.

The vent valve has two functions: 1) To purge the system before start up, and 2) to vent the high pressure gases stored in various scrubbers and piping, thus relieving the compressor of back pressure and back rotation during an emergency shutdown.

DESIGN ARRANGEMENT

The components and systems are arranged in a double-deck platform as shown in Figure 2. The overall dimensions are: length 54 ft., width 35 ft., height 46 ft., and weight 365 tons. The lower deck consists of the air conditioned control room, the gas generator, power turbine, gearbox, two barrel compressors, lube and seal oil system, process valves and scrubbers. These are arranged as shown in Figure 3. Mounted in the top deck are the fin fan coolers, fuel system, glycol dehydrator, and after-scrubber.

Figure 4, which is a view of the bottom deck looking at the service end of high pressure compressor, shows the inlet and discharge pipes to the compressors, the scrubbers S1, S2, and S3, as well as the water sprinkler piping on the scrubbers, etc.

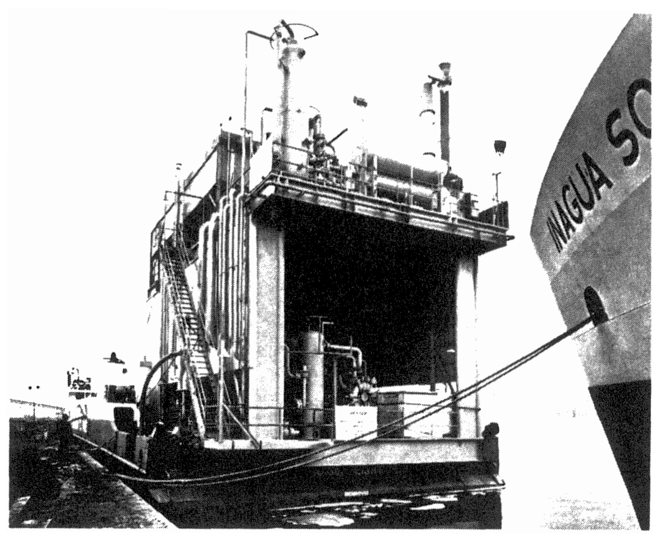


Figure 2. The Single Lift Package.

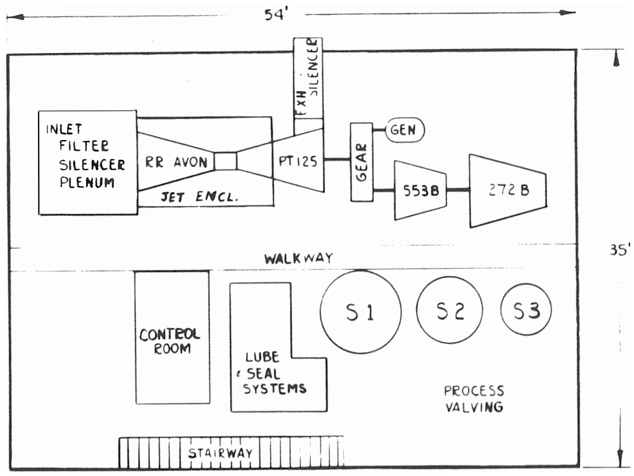


Figure 3. Arrangement on the Lower Deck.

Components—Description and their Rated Performance

GAS GENERATOR

The gas generator is a gas burning Rolls Royce Avon MK 1533-75G, as shown in Figure 5. This is an aircraft derivative engine derated to increase the time between over-all TBO, to above 20000 hrs. at base load. The base load ISO, 59°F and sea level, rating being 19400 EGHP. EGHP, exhaust gas horsepower, is the horsepower that could be produced by expanding the gases isentropically (efficiency = 100%) to ambient pressure through a turbine. The inlet system to the engine consists of a filter, a silencer, and a plenum chamber. The gas generator is started using a gas expander. The expanded is housed inside the plenum chamber and drives a shaft through the inlet bullet nose of the engine.

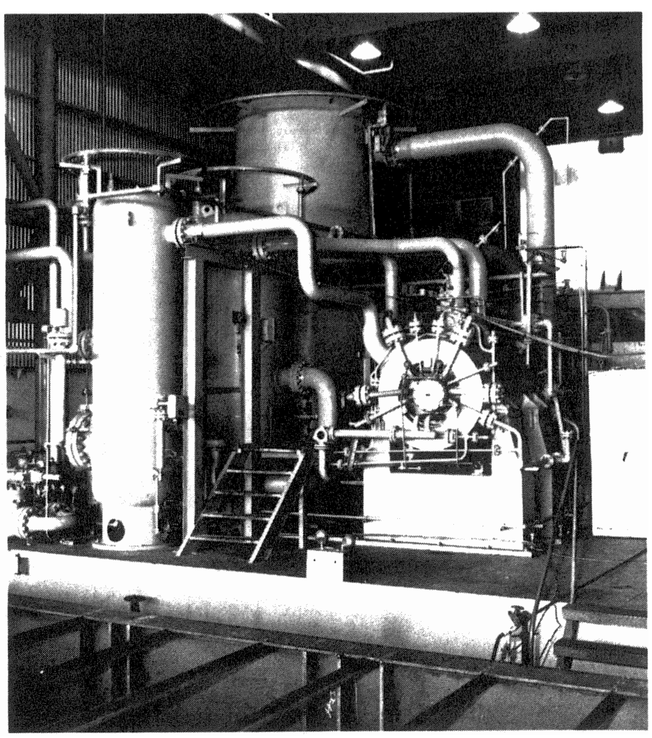


Figure 4. View-Looking at Service End of Dresser-Clark 272B6/4 Compressor.

FREE POWER TURBINE

This is a Dresser Clark Model PT 125 single stage turbine with adjustable stator to facilitate matching of any of the other gas generators in this power class like Pratt & Whitney GG3 and GE LM 1500.

Figures 6 and 7 show a perspective and a sectional view of the turbine. The exhaust gases are ducted horizontally to a side of the platform and vertically clearing the coolers on the top deck. The exhaust system includes a silencer.

Figure 8 shows the performance of the gas turbine (GG + PT or DJ 125). The NEMA rating of this unit is 13500 HP at a power turbine speed of 5330 RPM with a heat rate of 10,000 BTU HP-HR.

GEARS

This is a speed increasing high speed gear drive with helical gears and has a gear ratio of 1.862. This is connected to power turbine and the compressors by gear type, continuously lubricated flexible couplings with hydraulic fits.

LOW PRESSURE COMPRESSOR

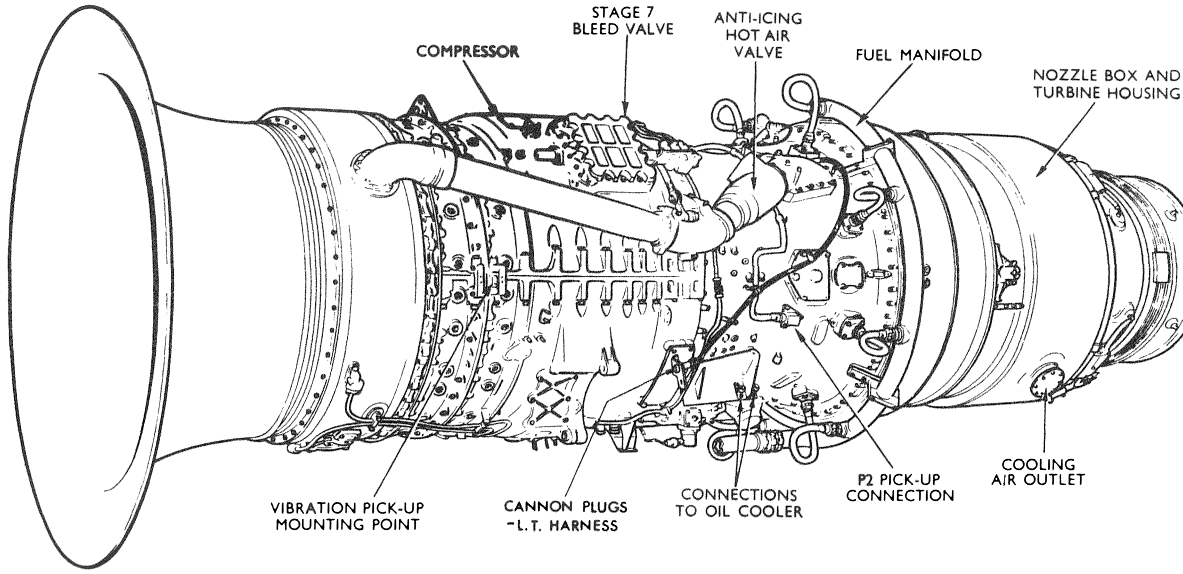
This is a barrel-type Dresser Clark Model 553B6, 6-stage centrifugal compressor. A balance piston is used to reduce the thrust on the thrust bearing. Two proximity type probes at each of the two tilt pad bearings serve to pick up the vibrations of the rotor. The design pressure ratio is 5.14 at an inlet flow of 8287 ACFM. The inlet pressure is maintained at 50 psig by a pressure control valve. Figure 9 shows the performance of this compressor.

HIGH PRESSURE COMPRESSOR

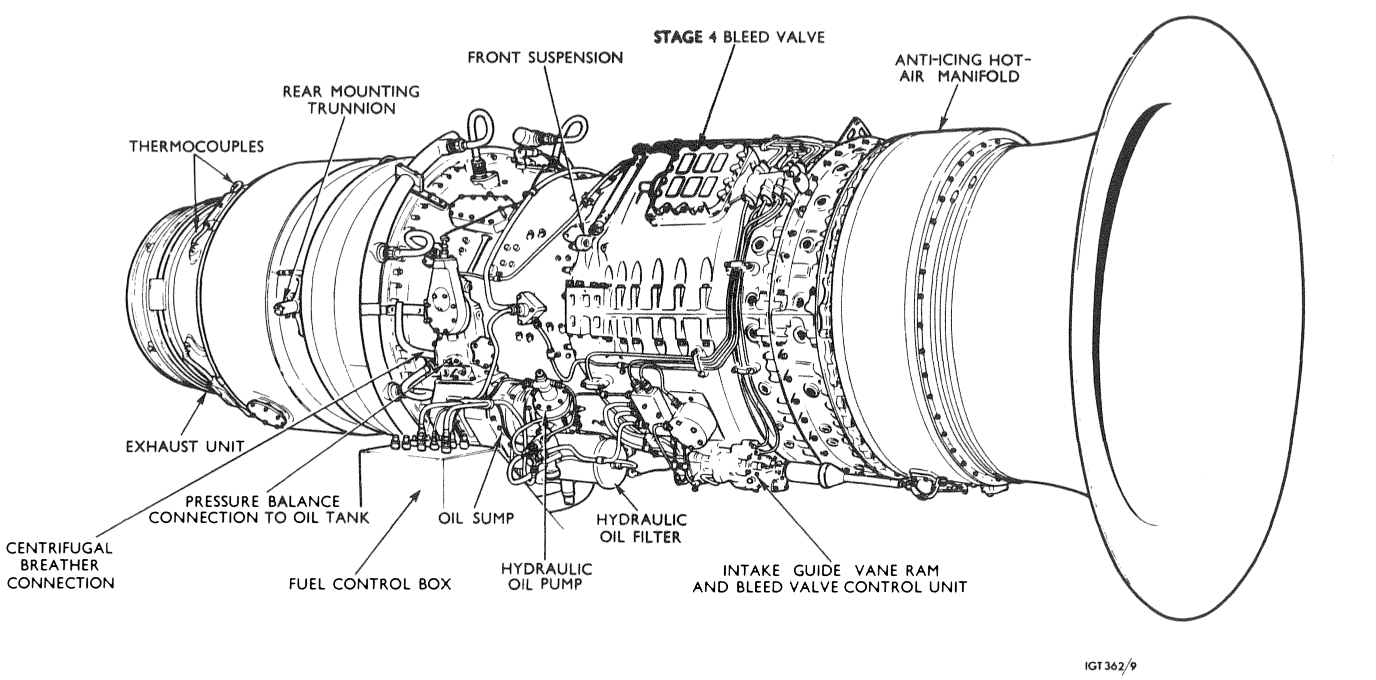
This is also a barrel type Dresser Clark Model 272B6 4 compressor with 6 + 4 stages arranged back to back to reduce the thrust. Figure 4 shows the inlet of the second section at the service end of the compressor and the final exit next to the exit of the first section illustrating the back-to-back arrangement. The gas is intercooled after six stages of compression. The thrust bearing is housed on the service end as shown in Figure 10. Two proximity type probes pick up the vibrations at the two tilt pad bearings. The drain oil temperatures are monitored continuously and recorded. The design conditions and the operating range are as shown in Figure 11.

COOLERS

The two intercoolers, the aftercooler and the lube oil cooler are all of fin fan type air coolers. The fans are driven by four 50 HP electric motors. The electric power is normally drawn from 250 KW generator which



LEFT-HAND VIEW OF ENGINE



RIGHT-HAND VIEW OF ENGINE

AVON GAS GENERATOR WITH GAS FUEL SYSTEM
(Shown with intake flare)

Figure 5. Gas Generator.

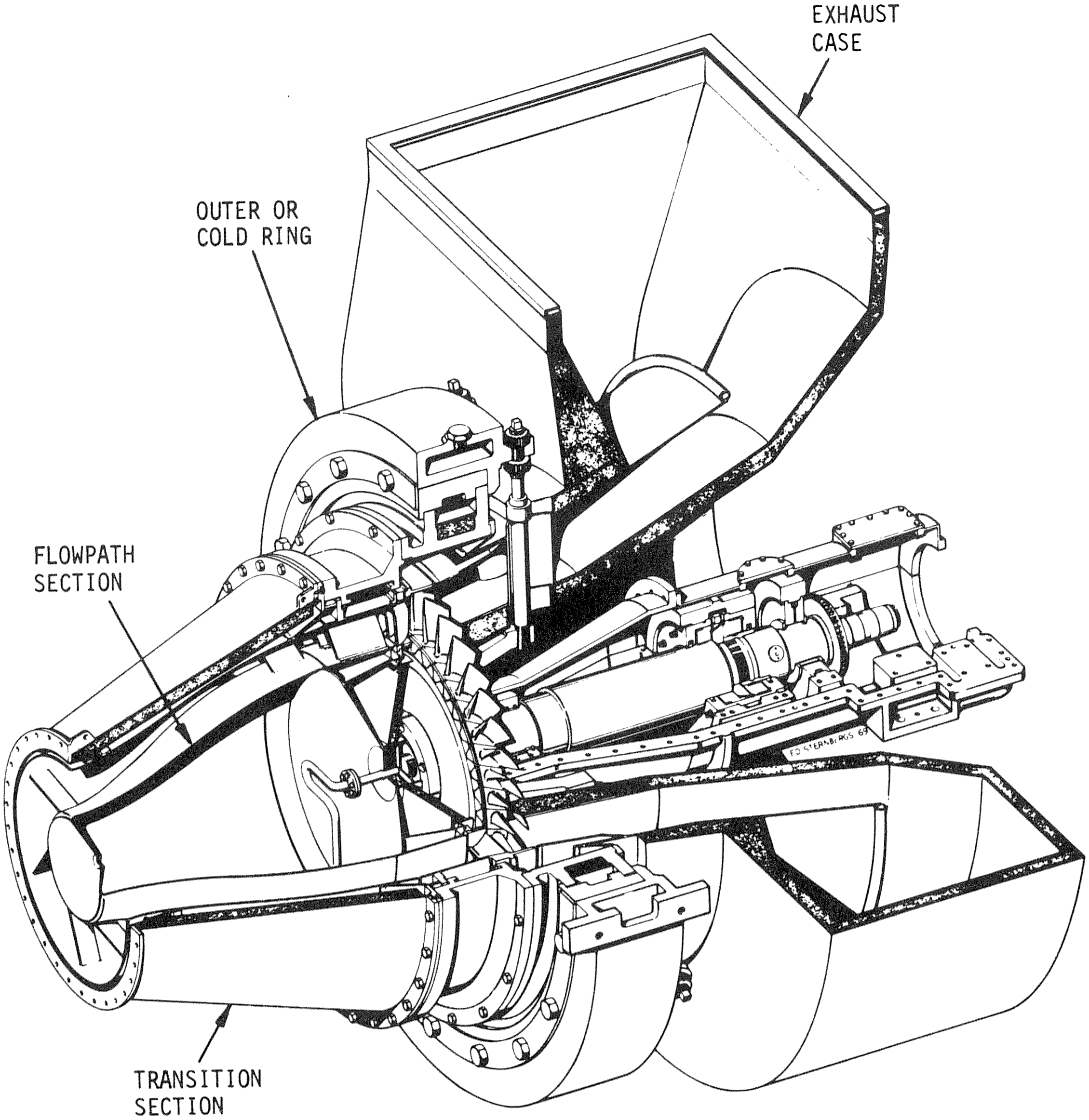


Figure 6. Cutaway—PT 125 Power Turbine.

is driven off one of the output shafts of the main gear drive. The process gas coolers have a pressure drop of 10 to 15 psi.

PROCESS SCRUBBERS AND VALVES

The scrubbers are designed to an ASME vessel code. Each vessel is provided with a relief valve set at the corresponding over-pressure. The vented gas through these relief valves joins a vent pipe and is piped away from the platform. The liquid levels are controlled by float type valves which discharge the liquids in a sequence from a high pressure low pressure vessel and finally to a sump.

All the process valves are mounted on the lower deck and are pneumatically operated. The opening and closing of inlet, discharge and vent valves are built into starting and shutdown sequence. The pressure control valve, PCV, is a butterfly type and is housed at the exit of scrubber S1, as seen in Figure 4. The recycle valves and the temperature control valve, TCV, are mounted on the floor of the lower deck.

FUEL SYSTEM

The fuel is normally drawn from the process scrubber S2. The external source cuts in through a check valve if the process pressure is lower than that of the external source. The system is housed on the floor of the top deck and consists of positive shut-off valves, regulator, filter, liquid trap, relief valve set at 280 psig, and a flow measuring orifice.

CONTROL SYSTEM

The control panel, Figure 12, is located in the control room. It is a free-standing design containing all the necessary protective relays, timing circuits and mode

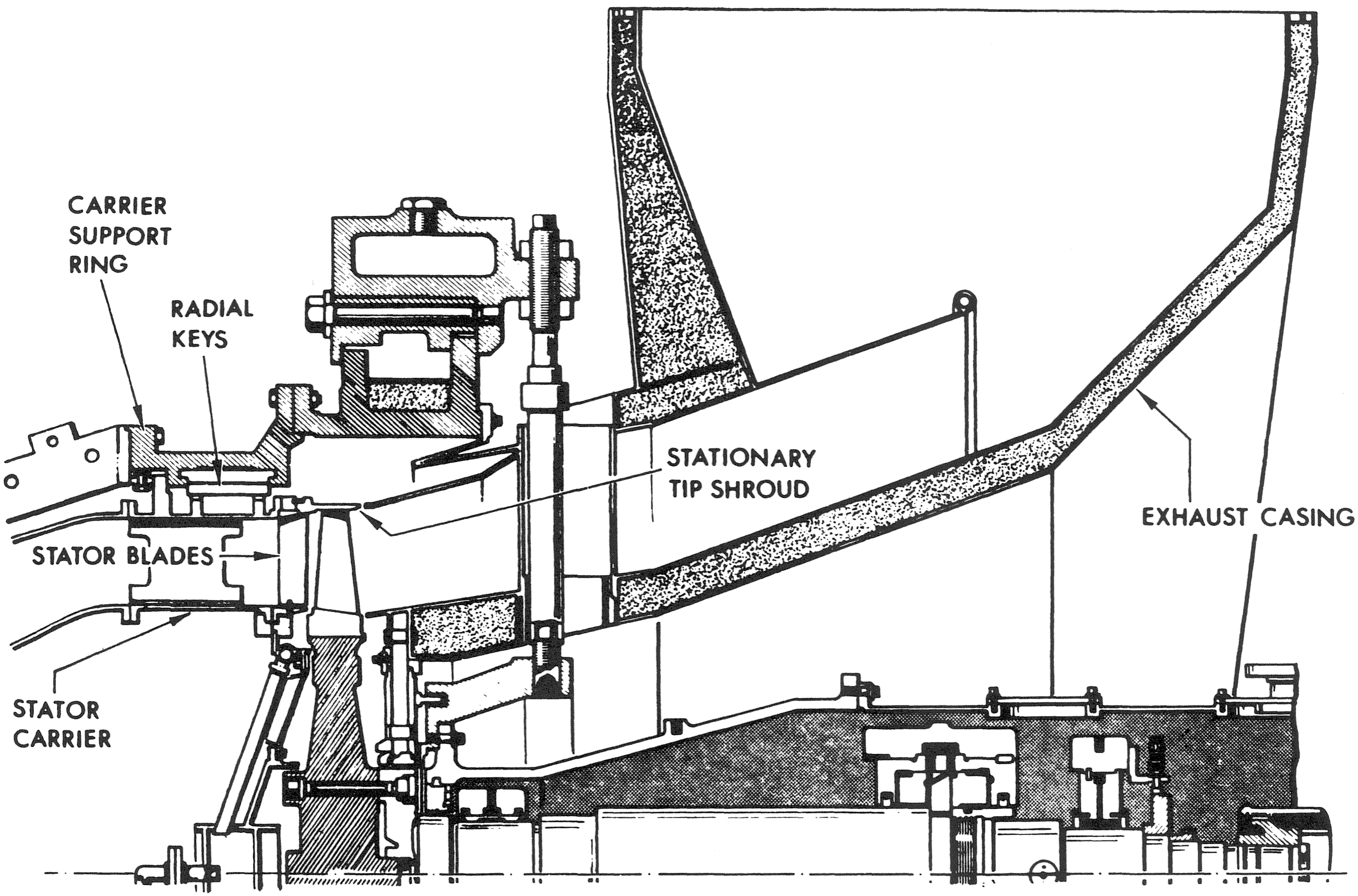


Figure 7. Cross Section—PT 125 Power Turbine.

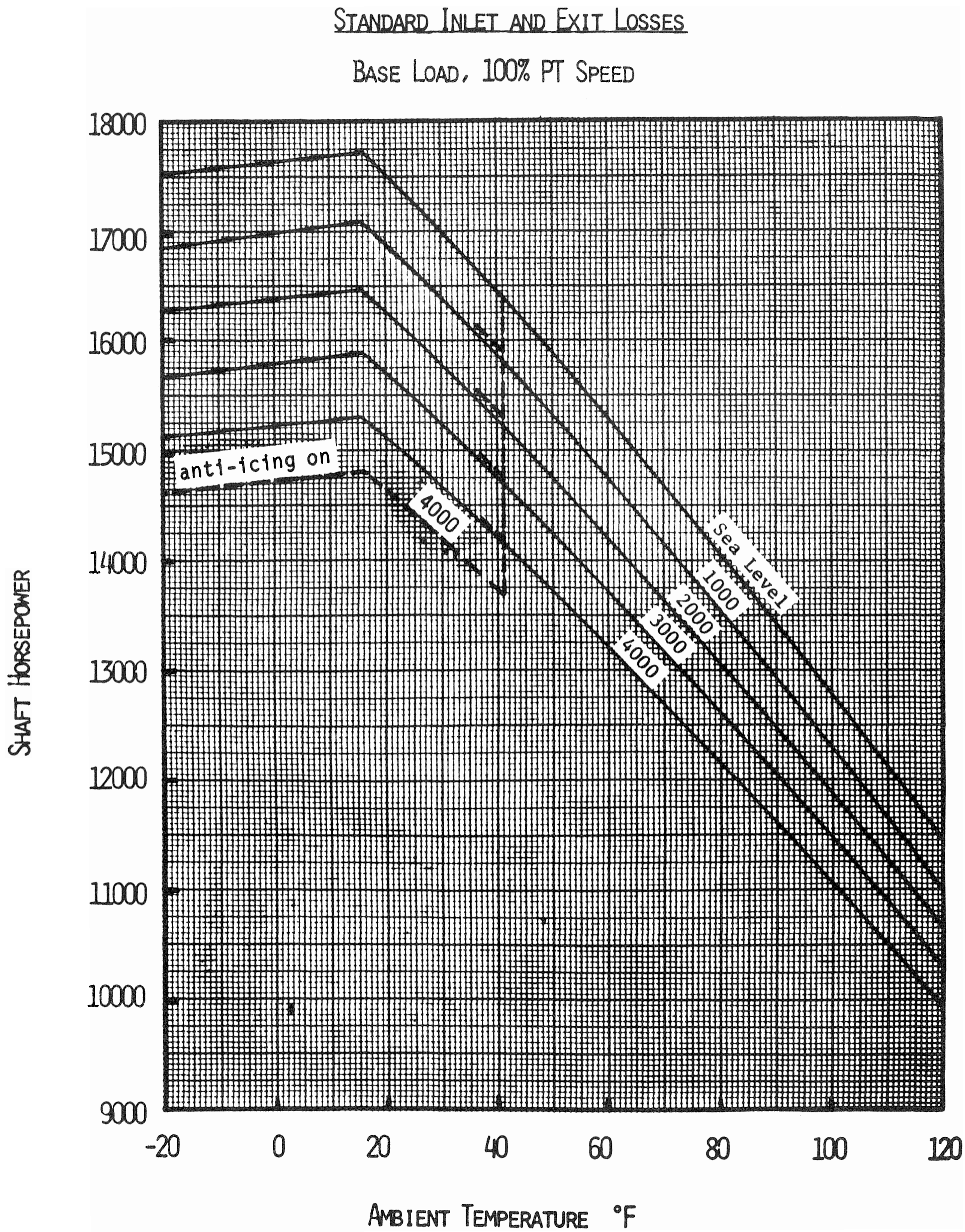


Figure 8. Performance—Dresser-Clark DJ 125 Gas Turbine.

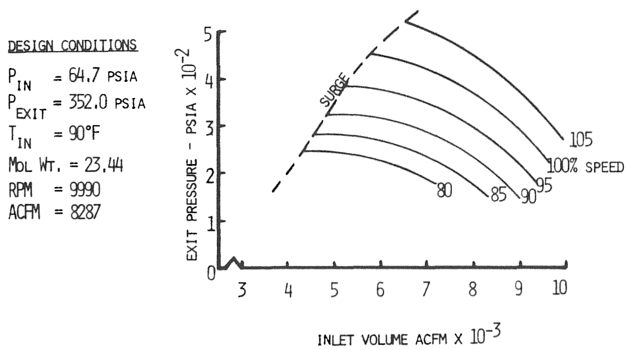


Figure 9. Map of 553B6 Compressor.

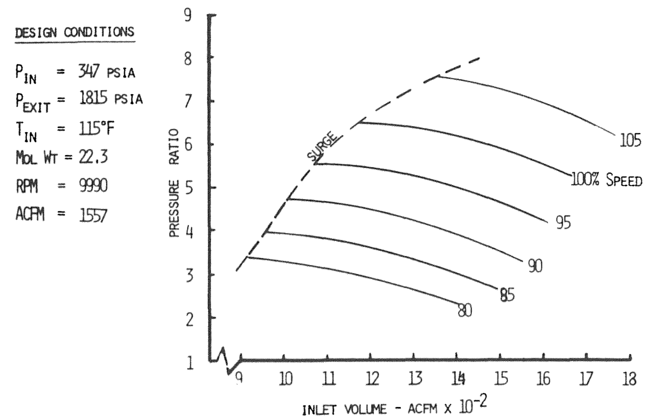


Figure 11. Map of 272B6/4 Compressor.

selector switches for safe operation of the unit. The normal design philosophy of fully automatic, self-protective system which sequences and controls the unit throughout the operating range is used. Figure 13 illustrates the basic control system. The primary loop is pressure control. Speed and temperature control loops are incorporated for machine protection and will override the pressure control if the load demand exceeds the gas turbine capability. The set point of each temperature and speed controller is placed at the maximum continuous value for optimum machine life. The system is basically electronic with a conversion to pneumatic and then hydraulic at the final control element on the gas generator. The sequencing system which monitors startup and shutdown and the unit protective devices are powered by a 24V battery supply.

In addition to the temperature, speed, and vibration monitors located on the face of the panel, there are annunciator lights to indicate the operating condition of the unit. The necessary relays for logic and malfunction indication are contained inside the panel. With the exception of the gas generator, all unit-mounted wiring and electrical devices are designed in accordance with the National Electrical Code, Class 1, Group D, Division 1 requirements.

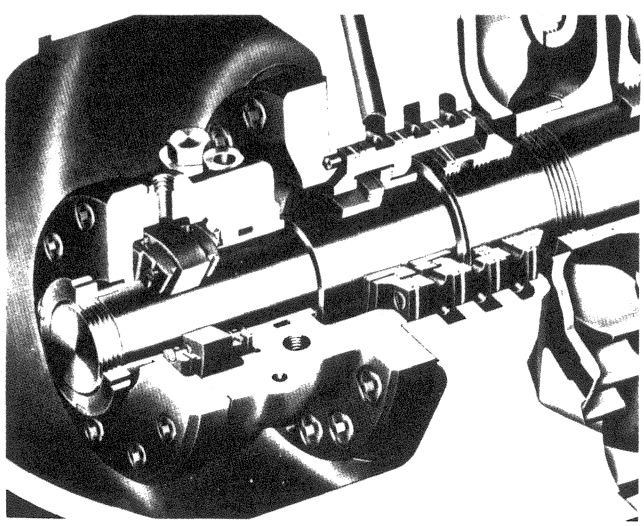


Figure 10. Cutaway—Compressor's Seals and Bearings.

LUBE AND SEAL OIL SYSTEMS

There are two systems: one for gas generator and one for power turbine, gear drive and compressors. The gas generator lubrication system consists mainly of a 50-gallon reservoir, 8-gallon hopper, a demister, duplex filters and coolers. The oil level in the GG sump, same as that in the 8-gallon hopper, is maintained by a float valve which draws oil from the reservoir by gravity. Low level alarm for the reservoir is set to give enough pre-warning to allow several days before the reservoir need be filled.

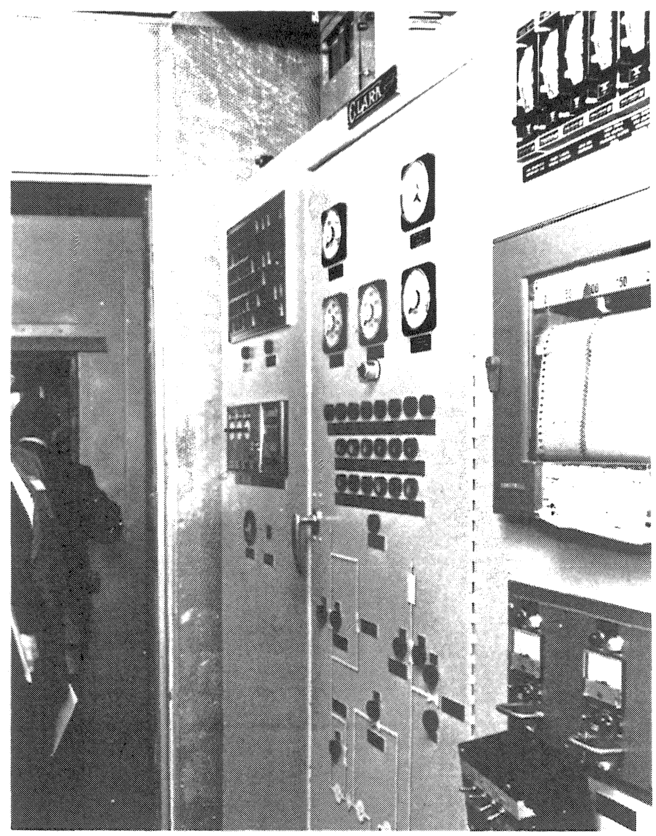


Figure 12. Control Panel.

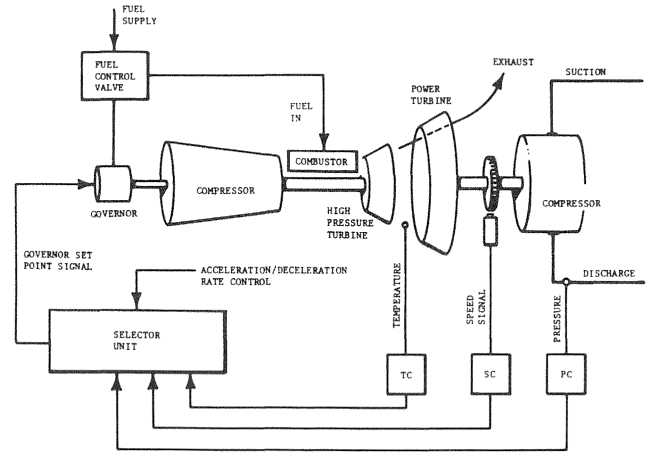


Figure 13. Basic Control System.

The turbine, gear drive, and compressor lube and seal oil system have two back-up pumps and a main pump. The main pump will normally be in service while the auxiliary and emergency pumps are off. Each pump is capable of maintaining approximately 150% maximum supply required. If the float of the operative pump falls below 125% of the capacity, the other pump will start automatically. Each pump is equipped with individual relief and isolation valves. Air or gas driven emergency pump will supply sufficient oil for run-down and cool-down when neither of the electric driven pumps is available. It is necessary to maintain an oil supply after shutdown to avoid overheating the forward bearing of the power turbine due to "soakback" from the disc. This flow is maintained for about two hours, which is why a pump takes the place of a tank for rundown. The lubrication circuit is as shown in Figure 14. As required, oil passes from any of the three pumps' discharge to the cooler: excess oil being bypassed through a back-pressure regulator and returned to the reservoir. The oil coolers that are mounted on the top deck are tube type air to oil. A temperature sensing three-way valve acts to bypass oil around the cooler as required to maintain the desired header temperature of about 120°F. After leaving the cooler circuit, the oil passes through a duplex filter assembly before being distributed to the bearings and seal oil tanks through one of the seal oil

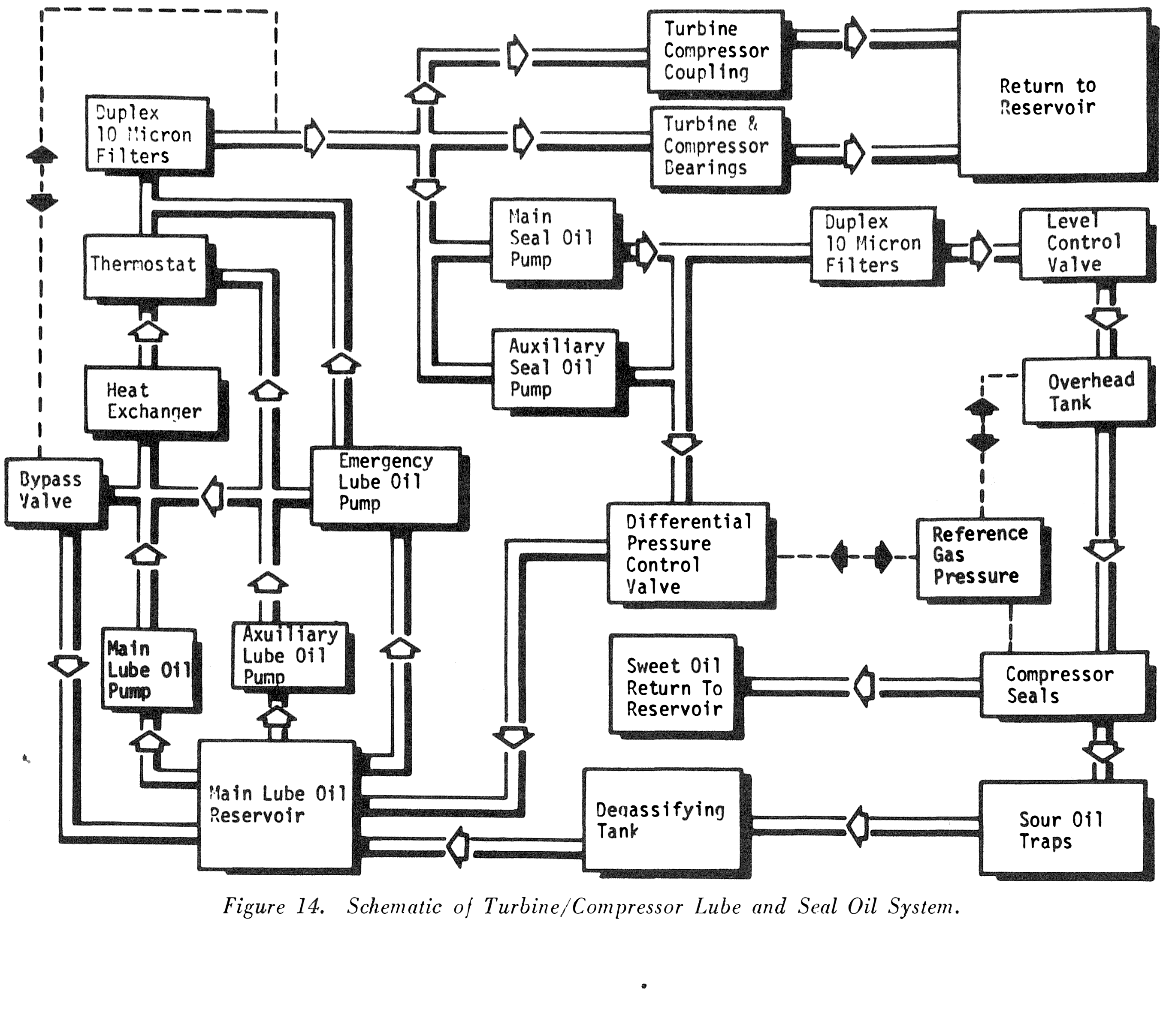


Figure 14. Schematic of Turbine/Compressor Lube and Seal Oil System.

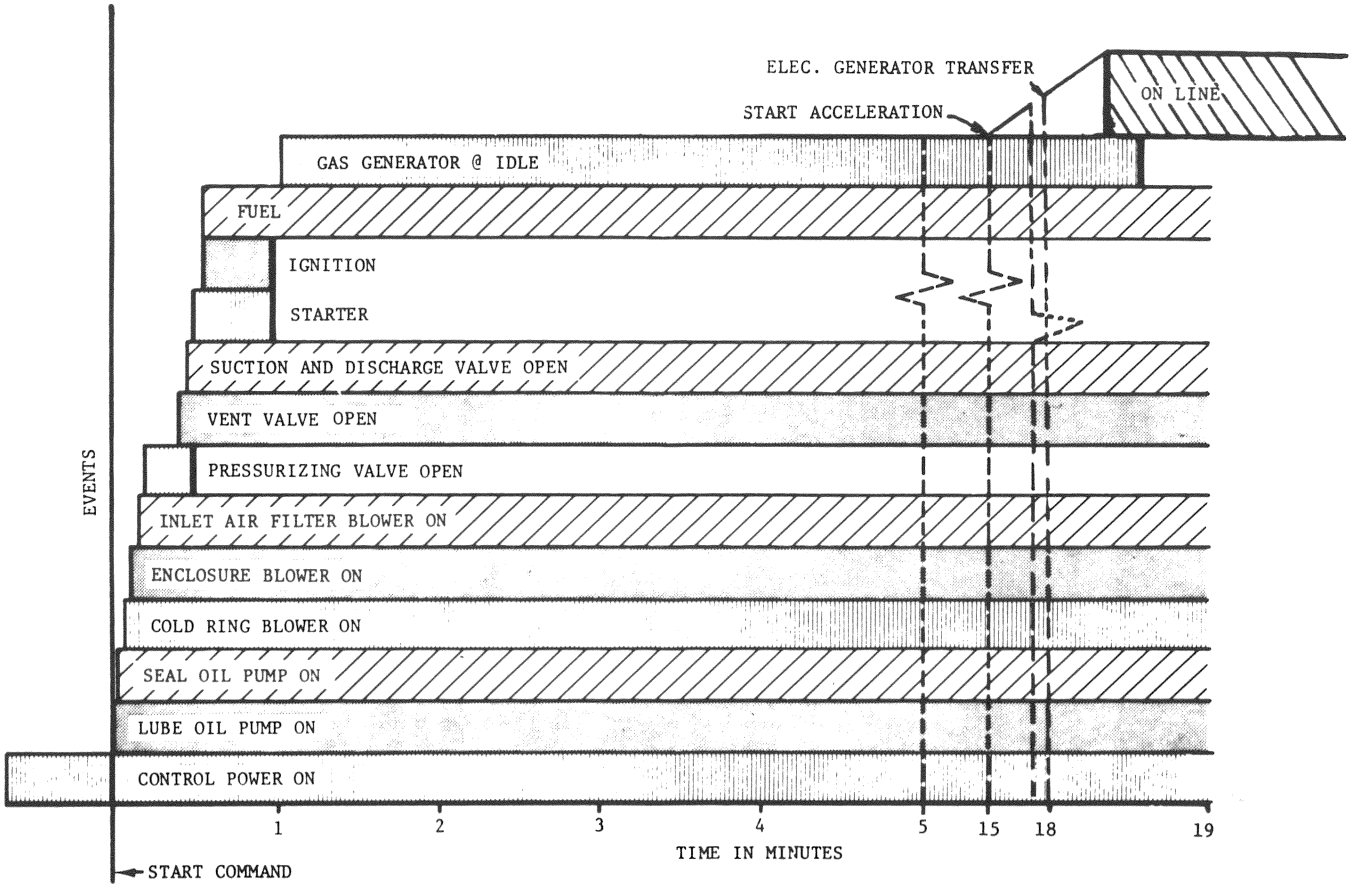


Figure 15. Starting Sequence.

pumps. The seal oil tanks maintain a gas to oil differential of 5 psi across the seals. Gravity drains from the bearing cases to the tank complete the cycle.

STARTING SEQUENCE

Figure 15 illustrates the starting sequence. The unit may be started by contact closure from a remote location or by pushbutton actuation on the control panel. The sequence, once initiated, is automatic, as follows:

1. Auxiliaries are started.
2. Unit valves are programmed.
3. System is pressurized.
4. Gas generator starter is energized.
5. Ignition occurs.
6. Unit accelerates to idle, gas generator at 3400 RPM, power turbine at 1200 RPM. a. Starter is disengaged; b. Ignitor is de-energized; c. Warm-up timer energized (15 minutes).
7. Unit accelerates at end of warm-up period at a rate determined by acceleration rate control setting until discharge pressure controller regulates the signal to the governor.
8. During acceleration the recycle valves are fully open till the unit attains a certain discharge pressure. Then the recycle valves automatically take over control and start closing as the gas turbine puts out more power to meet the demand of the controller.
9. The unit is fully on line.

Time relays will abort the sequence if any of the functions are not fulfilled within the pre-set time. For example, if the gas generator exhaust gas temperature does not record at least 450°F in ten seconds after the ignition signal, the sequence will be aborted.

PROTECTIVE DEVICES

The whole unit is protected from the following hazards:

1. overspeed
2. high pressure
3. high temperature
4. fire
5. surging of compressors
6. excessive vibration
7. lube oil failure and consequent high bearing temperatures
8. high liquid levels in scrubbers

9. proper deceleration during an emergency shutdown caused by any of the malfunctions causing a shutdown, etc.

10. hazardous atmosphere

Each of the components are protected from any or all of these possible hazards.

The gas generator is protected from excessive vibrations, low fuel gas pressure, high liquid level in the filter, alarms and shutdowns due to low or high lube oil level, in addition to overspeed and overtemperature, etc. The gas generator is enclosed in an acoustic enclosure and kept at moderate temperatures by a fan blower. A thermal fire sensing element triggers the emergency shutdown as well as carbon dioxide fire extinguisher system.

Fusible links, set to fuse at 260°F, close, allowing louvers to contain the carbon dioxide being sprayed inside the enclosure.

The control room is air-conditioned and is equipped with a smoke detector and a combustible mixture detector. The combustible mixture detector will both alarm and shut the unit down depending upon the strength of the mixture.

To protect the power turbine from dangerously excessive speed in case of an abrupt drop in load, an overspeed trip set at 110% of design RPM is built into the emergency shutdown circuit. This overspeed trip was required even though the power turbine speed is one of the controller set points of the basic control system. The three drain oil bearing temperatures are a measure of bearing temperatures and are monitored and recorded continuously. An emergency shutdown is initiated if any of these temperatures reach a pre-set value. A velocity pickup serves as a vibration monitor and the amplitude is displayed in the control room. Vibration levels are alarmed at pre-set levels and the unit is shut down in the event of excessive vibration.

Vibrations on the gearbox are sensed by a velocity pickup. Alarm and shutdown are executed at pre-set levels, and the amplitude is displayed in the control room. The six bearing drain oil temperatures are continuously recorded. The unit will be shut down if any of these temperatures exceed a pre-set value.

All the scrubbers are protected from excessive pressure by relief valves. They are also protected against overheating in case of a fire by a thermal sensing element which activates the water sprinkler system.

Compressor Protection.

a. High vibration—by proximity type probes which measure the amplitude and frequency of the shaft near the four bearings. The amplitude is displayed in the control room. The alarms and shutdowns are initiated at pre-set amplitudes.

b. High bearing temperatures—The drain oil temperatures are continuously recorded and serve to alarm and shut down if excessive.

c. Seal leakage—The oil side pressures of the seals are maintained at 5 psi above the gas pressure across the seal by overhead tanks whose levels are controlled. Low and high level alarms are incorporated in addition to a low level shutdown.

d. Liquid entrainment—Automatic discharging of liquids from various vessels protects the compressor from any liquids entering the compressor. Each scrubber has a float operated valve and an alarm and shutdown are initiated if high liquid levels are experienced.

e. High discharge temperature — An emergency shutdown is initiated if the discharge temperature of the compressors reaches 390°F.

f. Surge—The surge control system is designed to enable running the compressors away from surge line by recycling the extra flow required if the process line flow were to drop. The valves are controlled to enable the compressors to follow the control line automatically by sensing the differential static pressure, ΔP_f, across the inner and outer radii of a 90° bend which measures the volume flow through the compressor and by sensing a differential pressure, ΔP, across the compressor. The equation of the control line in the control range from about 80% speed to 105% speed is given by

$$\Delta P_{\text{compressor}} = K_1 \, \Delta P_f + K_2 \qquad (1)$$

where K_1 and K_2 are constants that depend upon the elbow size, gas gravity, compressor characteristic, etc. The surge control system becomes effective only above a pre-set pressure differential across the compressor. Below this, the recycle valves are kept open so as to keep the compressor away from the surge during startup and shutdown. The recycle valves are sized for full design flow in order to facilitate the testing of this platform at design condition in essentially two closed loops.

g. Low inlet temperature—The high pressure compressor, 272B, is protected from excessively low inlet temperatures when the unit is on recycle through the use of a thermal control valve, TCV. This TCV bypasses the required amount of hot gases to the inlet of RCV 2 and maintains a set temperature of 115°F at the inlet of 272B6 4 compressor by sensing the temperature downstream of RCV 2. An additional thermocouple senses the inlet temperature of 272 to cause a shutdown if the temperature drops below 65°F. This protection is not required across 553B compressor because of small drop in temperature due to Joule Thompson effect.

h. Excessive thrust and reverse rotation—The compressors are further protected from reverse rotation and high thrust condition on 272B during an emergency shutdown. This is accomplished by 1) sizing the vent valve as a compromise between high thrust and reverse rotation and opening it at the instant of an emergency shutdown; 2) delaying the closing of the station inlet valve; and, 3) opening the recycle valves instantaneously on an emergency shutdown.

Hand-operated liquid drain valves are installed at several places in order to purge the system of any liquids that may accumulate.

TESTING OF COMPONENTS

Total testing was accomplished in four stages as follows:

1. Full load test of Dresser Clark Model DJ 125 gas turbine for mechanical integrity, controls, and performance in the closed loop test facility.

2. Performance tests of compressors 553B6 and 272B6/4 were conducted at full speed but under reduced pressures in a closed loop test facility. Mechanical tests were conducted on seal and bearing test rig that simulates the dynamics of the rotor.

3. The total platform package was tested at full speed and reduced pressure conditions with low mol weight local natural gas and at full load conditions with natural gas and carbon dioxide mixture.

4. Final acceptance test at the site under field design conditions during February 1972.

GAS TURBINE

The purpose of this test was to insure the mechanical integrity, proper function of all controls of gas turbine, matching of free power turbine and the gas generator and measuring the power output at design conditions. The Houston test facility enables us to test gas turbines under full load conditions of up to 17,500 HP by using a pipeline compressor as the load device. The closed loop is designed for a maximum pressure of 1000 psia, and nitrogen is normally the working medium even though any desired combination may be used. The heat of compression or power is dissipated by heat exchangers using channel water. An electronic torque meter measures the power at the turbine shaft. A data acquisition system with 8K memory and magnetic tape device collects data and evaluates it by the use of pre-written programs while testing is in progress.

The performance evaluation showed that the unit would produce the required power at site and the heat rate would be better than expected. This test also showed that the matching between free power turbine and the gas generator could be improved before re-assembling the turbine on the platform in the slip.

COMPRESSOR TESTS

The closed loop facility in Olean, New York facilitates testing of compressors at full speed and at reduced pressure levels. Production tests were conducted in a closed loop using Freon 12 for 553B6 and nitrogen for 272B6/4 as the working mediums.

The results showed that the non-dimensional head-flow characteristics and the efficiencies were as expected. The vibrations were normal on both the inlet and discharge ends of the compressors. The surge line was also checked, both at high and low speeds, and was within the expected tolerance.

PLATFORM TEST IN THE SLIP

The platform was completely assembled in the slip and the test was conducted inside the slip. A special duct was built to dump the exhaust gases of the power turbine outside the slip.

The objectives of this test were: 1) to insure the mechanical integrity of the platform, 2) to demonstrate the satisfactory operation of the total rotating train: gas turbine, gear drive and compressors, 3) to eliminate the normal startup and assembly problems, 4) to calibrate the auxiliary and control systems, and 5) to verify the package performance.

Carbon dioxide was chosen as the gas to be mixed with the local natural gas in order to simulate the mol weight of field gas. The station inlet pipe was connected to the local gas line with a regulator. The platform was fully instrumented and included a gravitometer, pressure probes, etc., and the inlet pipe elbows were used to measure the volume flow through the compressors.

The process system was hydrotested to conform with the ASME code. A series of static and dynamic checks was made on the control system with the compressors uncoupled from the turbine. A complete control system check was made with the compressors coupled using natural gas alone, followed by a few intentional emergency shutdowns to ensure the operation of venting system, etc.

Many normal assembly and starting problems were corrected in addition to adjusting and calibrating of control circuit and auxiliary systems. The performance results indicated that the unit would exceed the design. The control system demonstrated that it would automatically start the unit, accelerate to full speed, shift electrical power to platform generator, control to any of the three settings on the controller and shut down on command.

COMMISSIONING THE UNIT ON SITE

The unit was shipped from Dresser - Packaged Compressor Division's slip with some precautionary measures, such as, disassembling the couplings, closing all intakes and discharges, sealing the control room, etc. The 365-ton platform was set on piles as seen in figure 16.

Though many of the normal starting problems in auxiliary and control systems were eliminated during

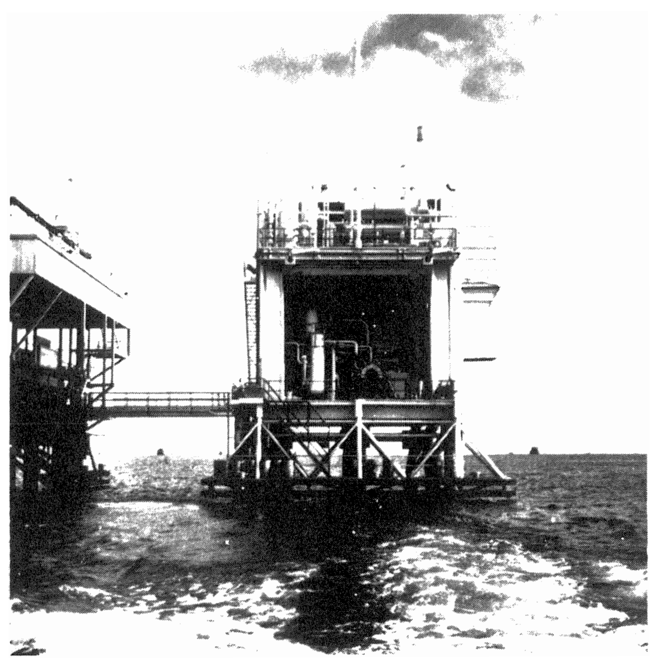


Figure 16. Dresser-Clark Single Lift Package on the Piles of Offshore Platform.

the platform test in the slip, a few checks like liquid knock-out systems, surge control system calibration, etc., had to be done on the site. The unit was run on recycles and data points were taken including gas samples in order to establish a surge control line for both compressors which would maximize the operating area.

During an emergency shutdown and a command shutdown, the high pressure gas contained in the process system was designed to be vented through the vent valve and through the station inlet valve by delaying the closing of the inlet valve. This calibration of inlet valve closing was demonstrated on site as this could not be done in the platform test on the slip.

Hot optical alignment readings were taken in order to evaluate the train alignment under running conditions. This was done by running the unit continuously on recycles for about 8 hours in order to thermally soak the unit.

The unit was checked for integrity of all devices. During these checks any engineering problems requiring engineering attention were analyzed and resolved by the engineering department.

The surge control system was set and the unit was put on stream in manual code but with the surge control system in automatic mode to ensure the proper takeover of the surge control system at the pre-set pressure and speed.

The unit was put on stream in late February 1972 and has been running continuously since then with no incident: results of the final performance test after being evaluated and reduced to design conditions showed that the unit exceeded the design flow by about 2 percent at the design discharge pressure and the heat rate was 5 percent better than design.

CONCLUSIONS

1. The advantages of custom-built platforms such as this, designed, manufactured and commissioned by one manufacturer, become evident in the expeditious handling of the design, testing, and commissioning of the unit.

2. The interaction and dependence of the components—compressor, turbine, controls, process system, etc. —on each other demonstrated the advantage of one engineering team being responsible for the analysis of the unit as a whole instead of separate components during design phase.

3. The importance and economics of pre-testing, and simulating field conditions as much as possible, were demonstrated by the number of problems corrected on the test stand prior to shipment.

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